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(71) Applicant
Dresser Industries Inc

(Incorporated in the USA - Delaware)

1600 Pacific Avenue, Dallas, Texas 75201,
United States of America

(72) Inventor
John G. Fischer

(74) Agent and/or Address for Service
Eric Potter & Clarkson
St Mary's Court, St Mary's Gate, Nottingham, NG1 1LE,
United Kingdom

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(54) Intersection solution method for drill bit design

(57) A process for distributing cutters along the profile of a drill bit and a drill bit produced by such a process is provided by which at least during one stage of bit design the cutters are distributed in a manner providing that each cutter traces a path of predetermined area. Two methods for determining that area are presented. The cutter distribution process provides for accurate cutter placement by taking into account each cutter's radial distance from the center line, respective placement along the profile, and intersection with other cutters. The placement of each cutter element along a conventional bit profile is determined by defining the bit profile in terms of a continuous line of alternately facing acute isosceles triangles the legs of which are equal to the cutter radius. The development of this geometry is achieved by the mathematical solution of the intersections of circles with lines and of circles with circles.

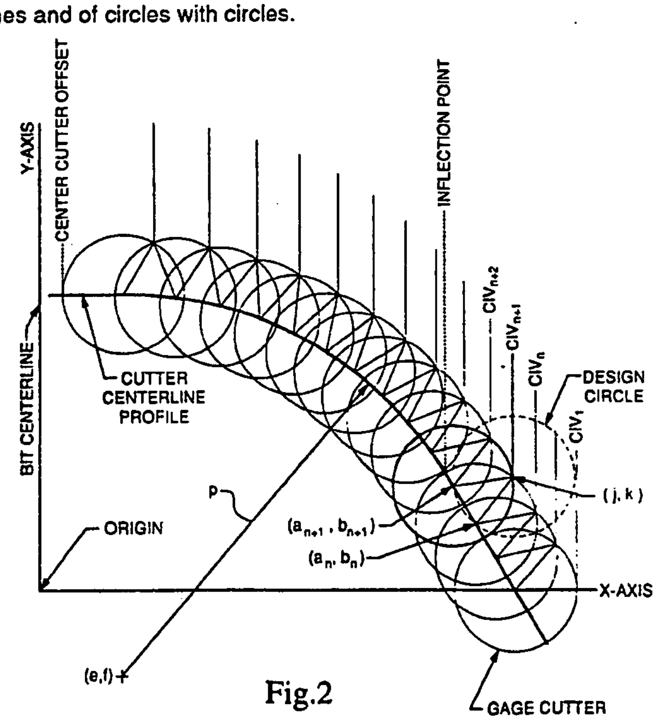

Fig.2

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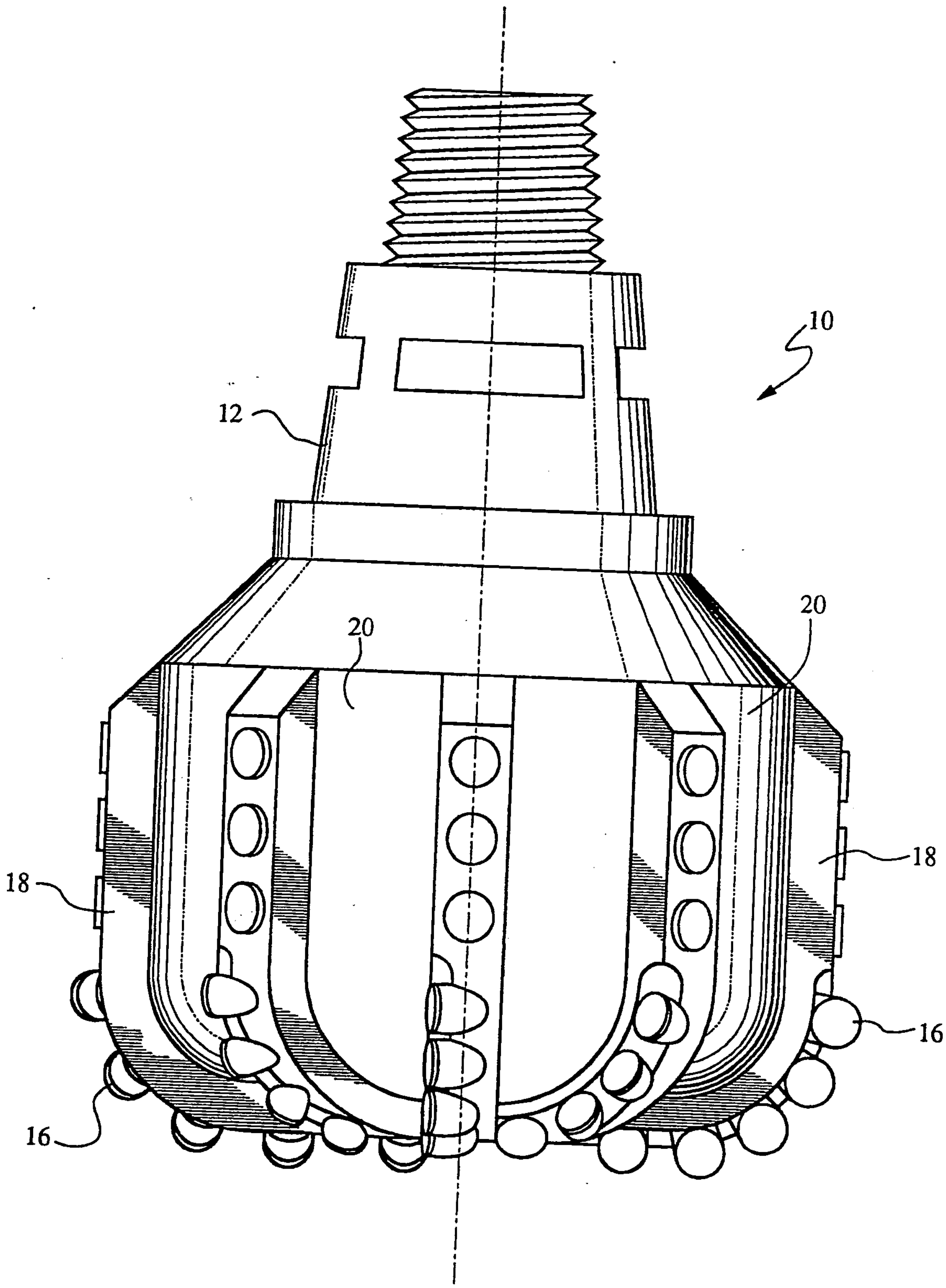

Fig.1

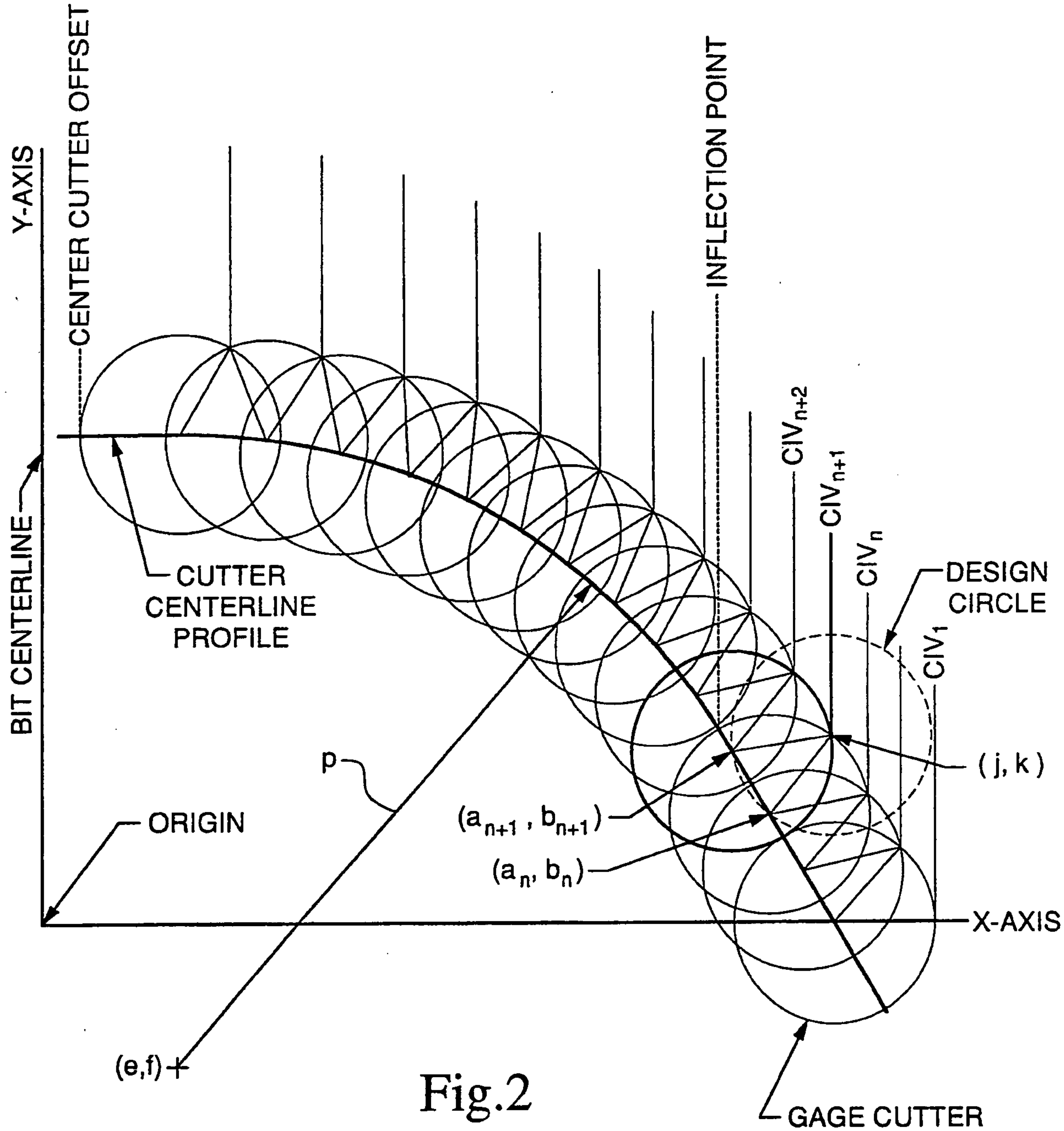
Y-AXIS
CENTER CUTTER OFFSET
INFLECTION POINT
BIT CENTERLINE
CUTTER CENTERLINE PROFILE
CIV_{n+2}
CIV_{n+1}
CIV_n
CIV_1
DESIGN CIRCLE
(j, k)
p
ORIGIN
(a_{n+1}, b_{n+1})
(a_n, b_n)
X-AXIS
(e,f)
GAGE CUTTER

Fig.2

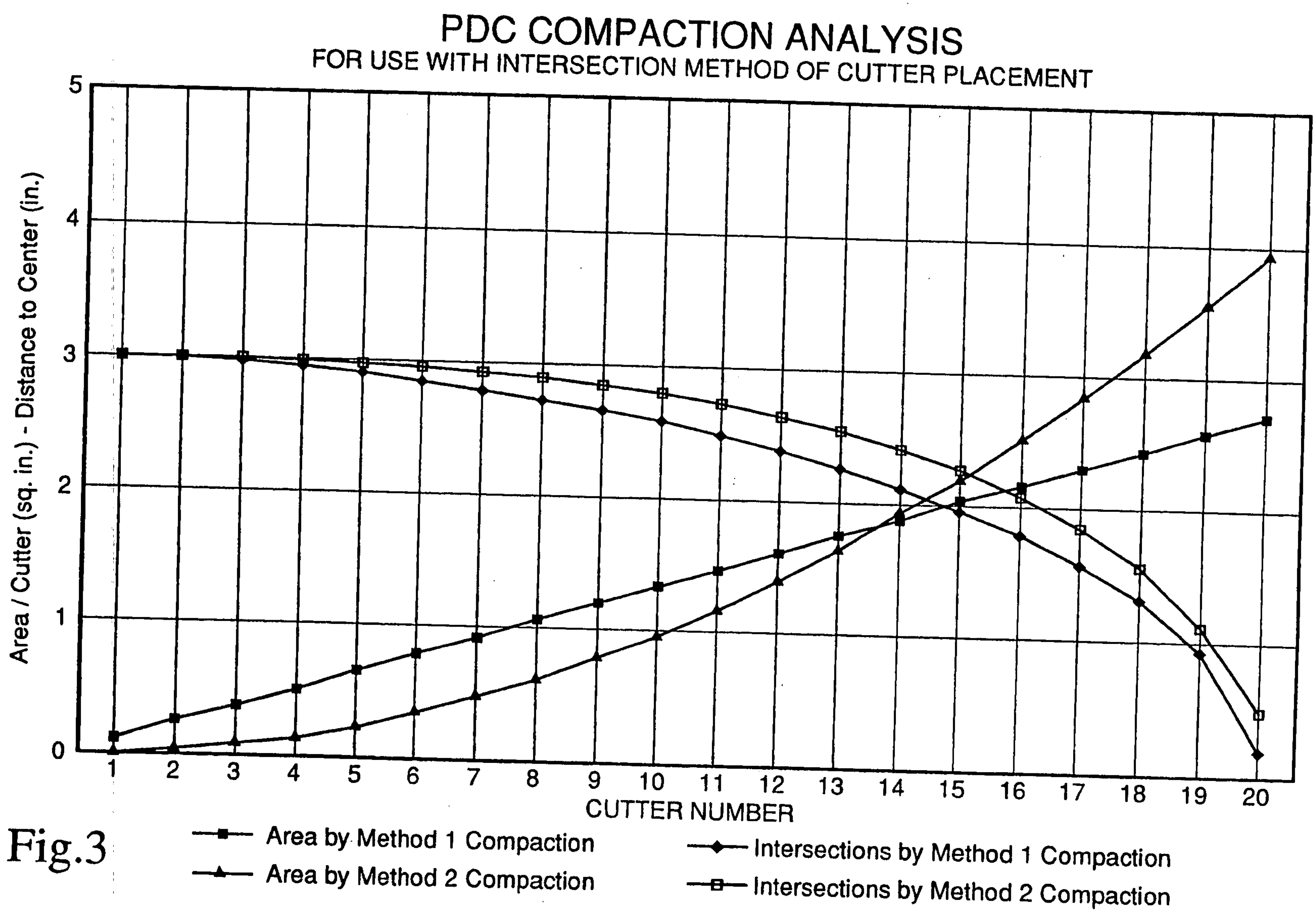
PDC COMPACTION ANALYSIS
FOR USE WITH INTERSECTION METHOD OF CUTTER PLACEMENT
Area / Cutter (sq. in.) - Distance to Center (in.)
0
1
2
3
4
5
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
CUTTER NUMBER
Area by Method 1 Compaction
Area by Method 2 Compaction
Intersections by Method 1 Compaction
Intersections by Method 2 Compaction

Fig.3

INTERSECTION SOLUTION METHOD FOR DRILL BIT DESIGN

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part of copending application Serial No. 07/485,311, filed on February 27, 1990.

BACKGROUND OF THE INVENTION

This invention relates to the design of drill bits and, more particularly, it concerns the distribution of earth boring cutting elements along the profile of a drill bit.

Conventional earth boring drill bits and particularly those commonly known as drag bits have cutting surfaces made up of a number of polycrystalline diamond-compact (PDC) cutters. Each of the PDC cutters is normally mounted on a tungsten carbide stud or cylinder which is received within a corresponding aperture of the drill bit during bit fabrication. PDC cutter elements such as STRATAPAX cutting elements from General Electric Company are readily commercially available.

The drill bit design and manufacturing industry has made a significant effort to distribute the individual cutters about the drill bit to provide the most efficient operation. In particular, a variety of methods and techniques have been developed so as to produce a cutter distribution which provides for uniform cutter wear in order to maximize the service life of the drill bit.

In the past, bit designers spaced cutters at uniform increments along radii extending from the central axis of the drill bit. Such a design has not been found to be completely effective since it does not take into account factors, such as, differing bit profiles, unequal cutter wear due to unequal volume cutting, and increased cutter wear related to higher cutter velocities.

An attempt to empirically determine an optimum cutter distribution is described in a technical paper

entitled "Optimization of Radial Distribution of STRATAPAX Cutters in Rock Drilling Bits" by J. D. Barr. This paper was presented to the Energy Sources Technology Conference at New Orleans in February, 1980. In this paper, a power law model is assumed to relate cutter wear rate to cutter velocity and area of cut and, thus, the distribution of cutters is made according to the formula: $1/S=K R$ where $E=b/c$. In this formula, S is the radial spacing between cutters, K is an empirical constant, R is the distance of the cutting edge from the central axis of the bit, E is a spacing exponent, b is a velocity exponent, and c is an area exponent. An upper limit for the value of S was selected at about 1/3 or 1/4 of the cutter diameter to insure adequate redundancy in the event of loss of a particular cutter or even two adjacent cutters. A disadvantage of the design method disclosed in this paper is a requirement for empirical wear measurements from used bits in the particular material to be drilled. Also, experiments undertaken by the author of the paper and summarized therein resulted in considerable scatter from theoretical wear patterns.

Another approach to the distribution of cutters on drill bits is described in a publication released by Sandia Laboratories entitled "Stratapax Computer Program" and authored by Richard F. Ashmore et al. The publication is identified by a number SAND77-1994 and was printed in April, 1978. This publication describes a complex computer program which calculates the volume of material cut by each cutter on a drill bit. A number of variables such as the location of the cutter in radial distance from the central axis of bit, the angular location of the individual cutters from an arbitrary base line in a plane perpendicular to the central axis of the bit and the position of the individual cutters along the length of the bit are input into the computer program. Then, the program optimizes the positioning of a number of cutters by trial and error iteration in an attempt to

achieve equal volume cuts for each cutter. This relatively complex program suffers from several disadvantages. For example, a system operator must first select a pattern of cutter distribution to initialize the computer program. This initial selection of cutter position effects the usefulness of the iteration technique.

A simplified approach to cutter placement in which a plurality of cutters are placed in a pattern approaching an ideal equal volume cutting arrangement while minimizing the mathematical steps necessary to calculate the desired positions is described in U.S. Patent No. 4,475,606 issued to Morgan L. Crow on October 9, 1984. This simplified approach positions the cutters so that the annular area between radially adjacent cutters as projected onto a common plane perpendicular to the central axis of the drill bit is a constant. Certain groups of cutters are positioned to prevent a central core in the material being drilled and to provide a desired kerf overlap. Although this approach produces drill bits having reasonable wear characteristics, it does not take into account variations in the bit profile, differences in wear due to different cutter velocities, and the actual intersection of the cutters with each other.

In light of the foregoing, there is a need for an improved process for accurately distributing cutters along the profile of a drill bit.

SUMMARY OF THE INVENTION

In accordance with the present invention, a process for distributing cutters along the profile of a drill bit and a drill bit produced by such a process is provided. The cutter distribution process of the present invention provides for accurate cutter placement by taking into account each cutter's radial distance from the bit center line, respective placement along the profile, and intersection with other cutters.

In the practice of the present invention, the placement of each cutter element along a conventional bit profile is determined by defining the bit profile in terms of a continuous line of alternately facing acute isosceles triangles the legs of which are equal to the cutter radius. The combination of isosceles triangles is developed by solving for a series of circle-line intersections and circle-circle intersections. This mathematical solution of intersections to represent a bit profile in accordance with the present invention applies to conventional bit profiles having a plurality of radially distributed cutter elements, but does not apply to center cutters and cases of extraordinary spread.

Among the objects of the present invention are, therefore, the provision of a process which provides a simple and yet effective solution for the distribution of cutters along the profile of a drill bit. Another object of the present invention is to provide such a process by which each cutter is distributed so as to trace a path of predetermined area taking into account their radial distances from the center line, their respective placement along the profile, and their intersection with each other. Yet another object of the present invention is to provide a drill bit having a cutter distribution which provides for uniform cutter wear and thereby maximizes the service life of the drill bit. Yet still another object of the present invention is the provision of a process for cutter distribution

which provides a more accurate cutter placement than is possible using conventional cutter placement techniques. Other objects and further scope of applicability of the present invention will become apparent from the detailed description to follow taken in conjunction with the accompanying drawings in which like parts are designated by like reference numerals.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a perspective view of an exemplary drill bit designed in accordance with the present invention;

Fig. 2 is a profile representation of the cutters on an exemplary drill bit rotated to a single radius from the central axis with variables identified as they appear in the equations in this application; and,

Fig. 3 is a chart illustrating two methods of PDC compaction.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In Fig. 1 of the drawings, an exemplary drill bit of the present invention is generally designated by the reference numeral 10 and shown to include a bit body 12 having a central axis of rotation 14. A plurality of individual PDC cutters 16 are mounted on respective wings 18 in a distribution that will be described hereinafter. The spaces 20 between the wings 18 permit drilling mud and cuttings from the working face to pass up along the gage of the bit and eventually to the surface for disposal in a conventional manner.

The distribution of the cutters 16 on the drill bit 10 is critical to the effective and efficient operation of the drill bit. If too much stress or wear is encountered on individual cutters, the drill bit can be rendered ineffective prematurely. Hence, the design goal is to achieve uniform wear on each cutter so as to maximize the service life and effectiveness of the drill bit.

Many conventional cutter distribution techniques do not take bit profile into account when positioning cutters. The result is that cutters do not cut equal paths or wear equally. A check of one bit showed errors greater than 13% in single revolution areas of coverage. Moreover, there is no way to automatically detect or correct errors. The cutter placement process of the present invention takes a more rigorous approach to accurate cutter placement which includes the evaluation of actual intersections of cutters along the real profile of the bit.

In accordance with the present invention and as shown in Fig. 2 of the drawings, cutter placement along a bit profile can be determined by solving equations for intersections of circles with lines and circles with circles. This is possible with the visualization of the profile being represented by a continuous series of

isosceles triangles whereas the legs of the isosceles triangles are equal to the radii of the cutters.

In accordance with the present invention and with reference to Fig. 2 of the drawings, during at least one stage of a bit design process cutter distribution is determined as follows:

I. Determine the geometry of the profile about an origin. Based in part on the desired cutter exposure.

BFP = Bit Face Profile

II. Determine the expressions for the loci of points through the center of the cutters and the inflection point at which changes in geometry take place.

CLP = Cutter Centerline Profile

III. Determine the amount of center cutter offset to be included, if any.

CCO = Center Cutter Offset (examples in this text will use 0)

IV. The below listed variables are recognized and the total area to be cut is determined:

R = Hole Radius

H = Hole Area

N = Number of cutters

n = Cutter Number (N to 1, descending)

r = Cutter Radius

A_n = Area assigned to cutter number n

Amax = Maximum Area for any cutter

Smax = Maximum Separation of cutter intersections

$H = 3.1416 \times (R^2)$

V. The limit of allowable separation of cutter intersections is determined. This distance is normally related to the Cuter Radius (r).

e.g. Smax = r

VI. Determine the area to be covered by each cutter preferably by a method of mathematical compaction. This process designates the area per cutter in such a way as to compensate for increases in wear as a result of the higher velocities cutter experience towards the outer perimeter of the bit. The compaction of the designated cutters takes place beginning with the maximum separation, along the length to be compacted. Two methods are shown in Fig. 3 of the drawings and will be demonstrated here. The first method involves the use of the sums of powers of integers. The second method uses a linear compaction with adjustable slope.

i. Method 1:

This method determines cutter area assignments by use of the 'Sums of the Powers of the Integers' with the equation for the first power demonstrated. This method should be applied within the limits of maximum cutter separation as described above. The power used determines the rate of compaction.

$P = N(N+1)/2$

$A_n = (n/P) \times H$

ii. Method 2:

This method determines cutter area assignments by use of an assigned number of cutters determining a slope of compaction. Alternatively the slope of compaction can be standardized and the number of cutters determined therein. The slope determines the rate of compaction. By having adjustable compaction rates, corrections can be made for different drilling conditions.

$$H = N(y_1) + (N/2)\ (y_2-y_1)$$
$$H/N = (y_1) + (y_2-y_1)/2$$
$$y_1 = (2H/N) - y_2$$

$$I = y_1 - m(x_1)$$
$$M = (y_2-y_1)\ /\ (x_2-x_1)$$

let $x_1 = 1$

$x_2 = N$

$y_2 = \text{Amax}$

Substituting;

$$M = \text{Amax}-[(2H/N)-\text{Amax}]/(n-1)$$

With I and M solved for:

$$A_n = Mx_n + I$$

VII. Determine the Cutter Intersection Values (CIV) from the areas which have been calculated beginning with the gage cutter. This is done regardless of the method chosen to determine the area per cutter.

CIV_n = Cutter Intersection Value

$$CIV_1 = R$$
$$CIV_n = (CIV_{n-1}^2 - A_n/3.1415)^{1/2}$$

VIII. Locate the gage cutter center on the cutter centerline profile tangent to the gage. Assuming the origin is on the bit centerline with y = 0 at the center of the gage cutter, the center point is:

CCP_n = Cutter Centerpoint for cutter n

$$CCP_1 = (R-r, 0)$$
$$CCP_n = (a_n, b_n)$$

Example: For an 8.5" bit with a Cutter radius of .262:

$$CCP_1 = (4.25 - .262,\ 0)$$
$$CCP_1 = (3.988,\ 0)$$

IX. Determine the Circle-Line Intersection

This is the intersection between cutter number 1 (gage cutter) and the vertical line CIV_2.

CIP_n = Cutter Intersection Point

$CIP_n = (j,k)$

The Line is vertical therefore:

$CIV_{n+1} = X$

The circle is the cutter face:

$(X-a_n)^2 + (Y-b_n)^2 = r^2$

The intersection of the circle and line is the set of points which solves the equations for each simultaneously.

Substitute for X:

$(CIV_{n+1}-a_n)^2 + (Y-b_n)^2 = r^2$

This eliminates X from the equation. Expanding this equation into its polynomial form:

$Y^2 - 2Yb_n + [(CIV_{n+1} - a_n)^2 + b_n^2 - r^2] = 0$

This equation is quadratic in terms of Y. Let:

$A = 1$

$B = -2b_n$

$C = [(CIV_{n+1} -a_n)^2 +b_n^2 -r^2]$

It follows that:

$AY^2 + BY + C = 0$

Then:

$Y = [-B \pm (B^2 - 4AC)]/2A$

There are two real solutions to the equation. The solution for the larger value of Y is the only point of interest.

Example continued:

Let $CIV_2 = 4.16$ for this example.

$(X-3.988)^2 + Y^2 = .262^2$

Substitute $X = 4.16$

$Y^2 = .0390$

$Y = .1975$

$CIP_2 = (4.16, .1975)$

This is the simplified solution for the gage cutter.

X. Designate a temporary Design Circle about the Cutter Intersection Point just located $CIP_n = (j,k)$ center of the design circle (Figure 2). The radius of the design circle is the same as that of the cutter. The center of the Design Circle is located at the apex of the isosceles triangle. The equation for the Design Circle is:

$$(X-j)^2 + (Y-k)^2 = r^2$$

Example continued: The equation for the design circle is;

$$(X-4.16)^2 + (Y-.1975)^2 = (.262)^2$$

XI. Now solve for the equation of the cutter Centerline Profile. For a linear section of the profile, the equation describing that interval of the CLP is:

$$Y = MX + I$$

Let θ be the angle between the x-axis and the Cutter Centerline profile. Then:

$$M = \operatorname{Tan}\theta$$

$$I = -M(CIV_1 - r)$$

$$Y = \operatorname{Tan}\theta(X) - M(CIV_1 - r)$$

Example continued: The gage cutter lies on a bit profile of 60 deg. to the centerline. The equation describing this interval of the CLP is found as follows:

$4.25 - .262 = 3.988$

Slope (M) = Tan 60 = -1.7321

Y-Intercept (I) = 6.9076

$Y = -1.7321(X) + 6.9076$

XII. Determine the Circle-Line Intersection of the Design Circle and the Cutter Centerline Profile. This will locate the center of the next cutter.

Equation of the circle (from step X.):

$(X-j)^2 + (Y-k)^2 = r^2$

Expanded:

$X^2 + Y^2 - 2Xj - 2Yk = r^2 - j^2 - k^2$

Equation of the line (from step XI.):

$Y = MX + I$

Substituting:

$X^2 + (MX + I)^2 - 2Xj - 2(MX + I)k = r^2 - j^2 - k^2$

Expanded to polynomial form:

$X^2 + M^2 X^2 + 2XMI + I^2 - 2Xj - 2MXk - 2Ik = r^2 - j^2 - k^2$

Factoring out $(M^2 + 1)$

$(M^2 + 1)X^2 + (2MI - 2j - 2Mk)X + I^2 - 2Ik = r^2 - j^2 - k^2$

This equation is now in quadratic form and can be simplified for evaluation.

Let $A = (M^2 + 1)$

$B = (2MI - 2j - 2Mk)$

$C = I(I - 2k) - r^2 + j^2 + k^2$

It follows that:

$AX^2 + BX + C = 0$

Then:

$$X = [-B \pm (B^2 - 4AC)]/2A$$

The solution of the discriminant determines the number of intersections. There will be two real solutions. The two solutions will represent the centers of two cutters n, and n+1. The solution with the lower value of X is the point of interest and this point will become

$$CCP_{n+1} = (a_{n+1}, b_{n+1})$$

Example continued:

Equation of the design circle is:

$$(X-4.160)^2 + (Y-.1975)^2 = .262^2$$

Equation of the cutter center line is:

$$Y = -1.7321(X) + 6.9076$$

Substituting:

$$(X - 4.160)^2 + (-1.7321(X) + 6.9076 - .1975)^2 = (.262)^2$$

$$X^2 - 8.32X + 17.3056 + 3.0002X^2 - 23.2451X + 45.0254 = .0686$$

$$4.0002X^2 - 31.5651X + 62.262 = 0$$

$$X = [31.5651 \pm (996.356 - 996.241)^{½}]/8.0004$$

$$\Delta^2 = .3372$$

The discriminant is positive and therefore there are two real solutions, meaning that the circle intersects the line twice.

X = 3.988 This is the center of the gage cutter.

X = 3.903 This is the center of the next cutter.

XIII. As cutter positions progress inward from the gage, they may now reach the curved portion of the bit profile. The point at which the curved portion of the profile is tangent to the linear portion is referred to as the Inflection Point (Fig. 2). As the value of each cutter centerpoint is determined, the abscissa must be compared to the Inflection Point. If the abscissa of the cutter centerpoint is less than that of the Inflection Point, then the solution of the centerpoint must be recalculated using the equations for the intersection of two circles as is described below. It is recognized that a given bit design may include multiple inflection points as a result of multiple changes in geometry and that the principles disclosed herein still apply.

XIV. The equation for the CLP in the curved interval, is for a circle with center at point (e,f) and radius p, as related to the origin previously described:

$$(X - e)^2 + (Y - f)^2 = p^2$$

Therefore:

$$X^2 + Y^2 - 2Xe - 2Yf = C$$

Where:

$$C = p^2 - e^2 - f^2$$

XV. The equation for the Design Circle around CIP_n is:

$$(X-j)^2 + (Y-k)^2 = r^2$$

and:

$$X^2 + Y^2 - 2Xj - 2Yk = D$$

where:

$$D = r^2 - j^2 - k^2$$

XVI. Subtracting the two circle equations

$$2X(j-e) + 2Y(k-f) = C - D$$

$$Y = X\,[(e - j/k-f)] + [(C - D)/2(k-f)]$$

This is the equation of a line which intersects either circle at the same two points, the solution set will solve for both equations:

Let $M = (e - j)/(k-f)$
and $I = (C - D)/(k-f)$
$Y = MX + I$

Substituting this value into the equation of the Design Circle

$$X^2 + (MX+I)^2 - 2jX - 2k(MX+I) = D$$

Expanding into its polynomial form,

$$X^2 + M^2 X^2 + 2XMI + I^2 - 2Xj - 2MXk - 2Ik = D$$

$$(M^2 + 1)X^2 + (2MI - 2j - 2Mk)X + I^2 - 2Ik = D$$

XVII. Wherein this equation is quadratic in terms of X and the solution determines the number of intersections, let:

$A = (M^2 + 1)$
$B = 2(MI - j - kM)$
$C = I(I - 2k) - D$

$$AX^2 + BX + C = 0$$

$$X = [-B \pm (B^2 - 4AC)]/2A$$

The positive value of the discriminant indicates two real roots exist and therefore two points of intersection. A zero value of the determinant would indicate that one real solution exists and therefore circles are tangent.

The larger value of X corresponds to the X value of the previous cutter center CCP_{n-1}, and the

lower value will correspond to the next cutter center CCP_n.

Substitute the lower X value into one of the two equations for a circle to solve for Y.

Other criteria such as force analysis (a determination of the direction and magnitude of the forces acting on each of the PDC cutters), back rake (the angle between the diamond face and the perpendicular to the hole face), side rake (the angle between the cutter face and the radial line extending from the bit center to the face of the cutter), cutter geometry since PDC cutters are available in a variety of shapes and sizes, and cutter velocity during bit operation can be taken into account when selecting area to be cut. It will still be necessary to identify the intersections between cutters.

It appears impractical to design bits for a singular rock hardness as most designs drill several rock types under a variety of operating conditions (weight-on-bit, RPM, Hydraulics, etc.) on any given application. Moreover, most PDC bits have more than one geographical application for which they are designed. The simplicity of having an adjustable rate of compaction allows designers to make adjustments based on wear analysis of dull bits run in the area of interest.

Thus, it will be appreciated that as a result of the present invention, a highly effective process for determining the distribution of cutters along the profile of a drill bit and a drill bit produced in accordance with this process is provided and by which the stated objectives, among others, are completely fulfilled. It is contemplated that modifications and/or changes may be made in the illustrated embodiment without departure from the invention. Accordingly, it is expressly intended that the foregoing description and the accompanying

drawings are illustrative of a preferred embodiment only, not limiting, and that the true spirit and scope of the present invention be determined by reference to the appended claims.

Claims:

What is claimed is:

1. In a process for determining the distribution of cutters along the profile of a drill bit, said process including the step of determining the placement of cutters along the profile of the bit so that each cutter traces a path of predetermined area, the improvement comprising:

determining the area to be covered by each cutter by a method of compaction, and

determining the distribution of said cutters by representing the bit profile as a continuous line of sequentially inverted acute isosceles triangles, the legs of which are equal to the radius of the cutters, this being achieved by mathematical solution of the intersections of circles with lines and of circles with circles.

2. The process of claim 1, wherein the intersection of circles with lines and of circles with circles includes a circular representation of each cutter with vertical cutter intersection valve lines (CIV) representing intersection points of adjacent cutters.

3. The process of claim 2, wherein the center of a design circle having a radius equal to the radius of the cutters is located at the intersection point of a cutter intersection value line (CIV_{n+1}) and a circle defining the cutter (n).

4. The process of claim 3, wherein the intersection of circles with lines and of circles with circles further includes the intersection of the design circle with a cutter centerline profile at two points of intersection with one defining the center of a first cutter (n) and the other defining the center of an adjacent cutter (n+1).

5. The process for determining the distribution of cutters along the profile of a drill bit substantially as herein described with reference to and as shown in the accompanying drawings.

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